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Observation of Color-suppressed $\bar{B}^0 \rightarrow D^0\pi^0$, $D^{*0}\pi^0$, $D^0\eta$, and $D^0\omega$ Decays*

K. Abe⁹, K. Abe³⁶, R. Abe²⁷, I. Adachi⁹, Byoung Sup Ahn¹⁵, H. Aihara³⁸, M. Akatsu²⁰, Y. Asano⁴², T. Aso⁴¹, V. Aulchenko², T. Aushev¹³, A. M. Bakich³⁴, E. Banas²⁵, S. Behari⁹, P. K. Behera⁴³, A. Bondar², A. Bozek²⁵, T. E. Browder⁸, B. C. K. Casey⁸, P. Chang²⁴, Y. Chao²⁴, K. F. Chen²⁴, B. G. Cheon³³, R. Chistov¹³, S.-K. Choi⁷, Y. Choi³³, L. Y. Dong¹², J. Dragic¹⁸, A. Drutskoy¹³, S. Eidelman², Y. Enari²⁰, F. Fang⁸, H. Fujii⁹, M. Fukushima¹¹, N. Gabyshev⁹, A. Garmash^{2,9}, T. Gershon⁹, A. Gordon¹⁸, K. Gotow⁴⁴, R. Guo²², J. Haba⁹, H. Hamasaki⁹, F. Handa³⁷, K. Hara²⁹, T. Hara²⁹, N. C. Hastings¹⁸, H. Hayashii²¹, M. Hazumi²⁹, E. M. Heenan¹⁸, I. Higuchi³⁷, T. Higuchi³⁸, H. Hirano⁴⁰, T. Hojo²⁹, T. Hokuue²⁰, K. Hoshina⁴⁰, S. R. Hou²⁴, W.-S. Hou²⁴, S.-C. Hsu²⁴, H.-C. Huang²⁴, Y. Igarashi⁹, T. Iijima⁹, H. Ikeda⁹, K. Inami²⁰, A. Ishikawa²⁰, H. Ishino³⁹, R. Itoh⁹, H. Iwasaki⁹, Y. Iwasaki⁹, D. J. Jackson²⁹, H. K. Jang³², H. Kakuno³⁹, J. Kaneko³⁹, J. H. Kang⁴⁶, J. S. Kang¹⁵, P. Kapusta²⁵, N. Katayama⁹, H. Kawai³, H. Kawai³⁸, N. Kawamura¹, T. Kawasaki²⁷, H. Kichimi⁹, D. W. Kim³³, Heejong Kim⁴⁶, H. J. Kim⁴⁶, H. O. Kim³³, Hyunwoo Kim¹⁵, S. K. Kim³², T. H. Kim⁴⁶, K. Kinoshita⁵, S. Kobayashi³¹, H. Konishi⁴⁰, P. Krokovny², R. Kulasiri⁵, S. Kumar³⁰, A. Kuzmin², Y.-J. Kwon⁴⁶, J. S. Lange⁶, S. H. Lee³², D. Liventsev¹³, R.-S. Lu²⁴, T. Matsubara³⁸, S. Matsumoto⁴, T. Matsumoto²⁰, Y. Mikami³⁷, K. Miyabayashi²¹, H. Miyake²⁹, H. Miyata²⁷, G. R. Moloney¹⁸, G. F. Moorhead¹⁸, S. Mori⁴², T. Mori⁴, A. Murakami³¹, T. Nagamine³⁷, Y. Nagasaka¹⁰, Y. Nagashima²⁹, T. Nakadaira³⁸, E. Nakano²⁸, M. Nakao⁹, J. W. Nam³³, Z. Natkaniec²⁵, K. Neichi³⁶, S. Nishida¹⁶, O. Nitoh⁴⁰, S. Noguchi²¹, T. Nozaki⁹, S. Ogawa³⁵, T. Ohshima²⁰, T. Okabe²⁰, S. Okuno¹⁴, S. L. Olsen⁸, W. Ostrowicz²⁵, H. Ozaki⁹, P. Pakhlov¹³, H. Palka²⁵, C. S. Park³², C. W. Park¹⁵, H. Park¹⁷, K. S. Park³³, L. S. Peak³⁴, M. Peters⁸, L. E. Piilonen⁴⁴, J. L. Rodriguez⁸, N. Root², M. Rozanska²⁵, K. Rybicki²⁵, J. Ryuko²⁹, H. Sagawa⁹, Y. Sakai⁹, H. Sakamoto¹⁶, M. Satapathy⁴³, A. Satpathy^{9,5}, S. Schrenk⁵, S. Semenov¹³, K. Senyo²⁰, M. E. Sevior¹⁸, H. Shibuya³⁵, B. Shwartz², A. Sidorov², S. Stanić⁴², A. Sugi²⁰, A. Sugiyama²⁰, K. Sumisawa⁹, T. Sumiyoshi⁹, K. Suzuki³, S. Suzuki⁴⁵, S. Y. Suzuki⁹, S. K. Swain⁸, T. Takahashi²⁸, F. Takasaki⁹, M. Takita²⁹, K. Tamai⁹, N. Tamura²⁷, J. Tanaka³⁸, M. Tanaka⁹, Y. Tanaka¹⁹, G. N. Taylor¹⁸, Y. Teramoto²⁸, M. Tomoto⁹, T. Tomura³⁸, S. N. Tovey¹⁸, K. Trabelsi⁸, T. Tsuboyama⁹, T. Tsukamoto⁹, S. Uehara⁹, K. Ueno²⁴,

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Y. Unno³, S. Uno⁹, Y. Ushiroda⁹, K. E. Varvell³⁴, C. C. Wang²⁴, C. H. Wang²³,
J. G. Wang⁴⁴, M.-Z. Wang²⁴, Y. Watanabe³⁹, E. Won³², B. D. Yabsley⁹, Y. Yamada⁹,
M. Yamaga³⁷, A. Yamaguchi³⁷, H. Yamamoto³⁷, Y. Yamashita²⁶, M. Yamauchi⁹,
S. Yanaka³⁹, J. Yashima⁹, M. Yokoyama³⁸, K. Yoshida²⁰, Y. Yuan¹², Y. Yusa³⁷,
C. C. Zhang¹², J. Zhang⁴², Y. Zheng⁸, V. Zhilich², and D. Žontar⁴²

Belle Collaboration

- ¹Aomori University, Aomori
²Budker Institute of Nuclear Physics, Novosibirsk
³Chiba University, Chiba
⁴Chuo University, Tokyo
⁵University of Cincinnati, Cincinnati OH
⁶University of Frankfurt, Frankfurt
⁷Gyeongsang National University, Chinju
⁸University of Hawaii, Honolulu HI
⁹High Energy Accelerator Research Organization (KEK), Tsukuba
¹⁰Hiroshima Institute of Technology, Hiroshima
¹¹Institute for Cosmic Ray Research, University of Tokyo, Tokyo
¹²Institute of High Energy Physics, Chinese Academy of Sciences, Beijing
¹³Institute for Theoretical and Experimental Physics, Moscow
¹⁴Kanagawa University, Yokohama
¹⁵Korea University, Seoul
¹⁶Kyoto University, Kyoto
¹⁷Kyungpook National University, Taegu
¹⁸University of Melbourne, Victoria
¹⁹Nagasaki Institute of Applied Science, Nagasaki
²⁰Nagoya University, Nagoya
²¹Nara Women's University, Nara
²²National Kaohsiung Normal University, Kaohsiung
²³National Lien-Ho Institute of Technology, Miao Li
²⁴National Taiwan University, Taipei
²⁵H. Niewodniczanski Institute of Nuclear Physics, Krakow
²⁶Nihon Dental College, Niigata
²⁷Niigata University, Niigata
²⁸Osaka City University, Osaka
²⁹Osaka University, Osaka
³⁰Panjab University, Chandigarh
³¹Saga University, Saga
³²Seoul National University, Seoul
³³Sungkyunkwan University, Suwon
³⁴University of Sydney, Sydney NSW
³⁵Toho University, Funabashi
³⁶Tohoku Gakuin University, Tagajo
³⁷Tohoku University, Sendai
³⁸University of Tokyo, Tokyo

³⁹Tokyo Institute of Technology, Tokyo

⁴⁰Tokyo University of Agriculture and Technology, Tokyo

⁴¹Toyama National College of Maritime Technology, Toyama

⁴²University of Tsukuba, Tsukuba

⁴³Utkal University, Bhubaneswer

⁴⁴Virginia Polytechnic Institute and State University, Blacksburg VA

⁴⁵Yokkaichi University, Yokkaichi

⁴⁶Yonsei University, Seoul

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Abstract

We report the first observation of color-suppressed $\bar{B}^0 \rightarrow D^0\pi^0$, $D^{*0}\pi^0$, $D^0\eta$, and $D^0\omega$ decays and evidence for $\bar{B}^0 \rightarrow D^{*0}\eta$ and $D^{*0}\omega$. The branching fractions are found to be $\mathcal{B}(\bar{B}^0 \rightarrow D^0\pi^0) = (3.1 \pm 0.4 \pm 0.5) \times 10^{-4}$, $\mathcal{B}(\bar{B}^0 \rightarrow D^{*0}\pi^0) = (2.7^{+0.8}_{-0.7} {}^{+0.5}_{-0.6}) \times 10^{-4}$, $\mathcal{B}(\bar{B}^0 \rightarrow D^0\eta) = (1.4^{+0.5}_{-0.4} \pm 0.3) \times 10^{-4}$, $\mathcal{B}(\bar{B}^0 \rightarrow D^0\omega) = (1.8 \pm 0.5 {}^{+0.4}_{-0.3}) \times 10^{-4}$, and we set 90% confidence level upper limits of $\mathcal{B}(\bar{B}^0 \rightarrow D^{*0}\eta) < 4.6 \times 10^{-4}$ and $\mathcal{B}(\bar{B}^0 \rightarrow D^{*0}\omega) < 7.9 \times 10^{-4}$. The analysis is based on a data sample of 21.3 fb^{-1} collected at the $\Upsilon(4S)$ resonance by the Belle detector at the KEKB e^+e^- collider.

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Decay modes such as $\overline{B}^0 \rightarrow D^{(*)+}\pi^-$ were amongst the first B meson decays to be fully reconstructed. However, the $\overline{B}^0 \rightarrow D^{(*)0}h^0$ decay modes, where h^0 represents a light neutral meson, have not been observed to date. A recent search by the CLEO Collaboration [1] yielded only upper limits. As shown in Fig. 1, these decays are expected to proceed via an internal spectator diagram and be suppressed relative to decays proceeding via the external spectator diagram, since the color of the \overline{u} antiquark produced by the weak current must complement the color of the c quark. The contribution of the W -exchange diagram is usually assumed to be negligible [2]. Studies of such color-suppressed decay modes are useful for testing models of hadronic B meson decay and provide information on final-state interactions. Final state interactions, if also present in B decays to charmless modes, could have significant impact on CP violating rate asymmetries [3]. Furthermore, studies of $\overline{B}^0 \rightarrow D^{(*)0}h^0$ where the D^0 decays to a CP eigenstate will provide access to the CP violation parameter $\sin 2\phi_1$ in $b \rightarrow c\overline{u}d$ processes [4]. Thus, measuring the strength of color-suppressed modes can have profound implications on B physics and CP violation.

In this paper, we report on a search for the color-suppressed $\overline{B}^0 \rightarrow D^0h^0$ and $D^{*0}h^0$ [5] decays, where the neutral meson h^0 is either a π^0 , η , or ω . We make first observations of the modes $\overline{B}^0 \rightarrow D^0\pi^0$, $D^{*0}\pi^0$, $D^0\eta$, and $D^0\omega$ and find evidence for the modes $\overline{B}^0 \rightarrow D^{*0}\eta$ and $D^{*0}\omega$. The data used in this analysis were collected with the Belle detector [6] at KEKB [7], a double storage ring that collides 8 GeV electrons with 3.5 GeV positrons with a 22 mrad crossing angle. The data sample corresponds to an integrated luminosity of 21.3 fb^{-1} at the $\Upsilon(4S)$ resonance, which contains 23.1 million $B\overline{B}$ pairs, and 2.3 fb^{-1} taken 60 MeV below the resonance.

Belle is a general-purpose detector with a 1.5 T superconducting solenoid magnet. Charged particle tracking, covering 92% of the total center-of-mass (CM) solid angle, is provided by the Silicon Vertex Detector (SVD) consisting of three concentric layers of double-sided silicon strip detectors and a 50-layer Central Drift Chamber (CDC). Charged hadrons are distinguished by combining the responses from an array of Silica Aerogel Čerenkov Counters (ACC), a Time of Flight Counter system (TOF), and dE/dx measurements in the CDC. The combined response provides K/π separation of at least 2.5σ for laboratory momenta up to $3.5 \text{ GeV}/c$. Photons and electrons are detected in an array of 8736 CsI(Tl) crystals (ECL) located inside the magnetic field and covering the entire solid angle of the charged particle tracking system. The 1.5 T magnetic field is returned via an iron yoke, instrumented to detect muons and K_L mesons (KLM). The KLM consists of alternating layers of resistive plate chambers and 4.7 cm thick steel plates.

We reconstruct light neutral mesons h^0 using the $\pi^0 \rightarrow \gamma\gamma$, $\eta \rightarrow \gamma\gamma$, $\eta \rightarrow \pi^+\pi^-\pi^0$ and $\omega \rightarrow \pi^+\pi^-\pi^0$ decay channels. Charged tracks are required to have impact parameters that are within $\pm 5 \text{ cm}$ of the interaction point along the positron beam axis and 1 cm in the transverse plane. We reject tracks that are consistent with being electrons or muons. The remaining tracks are identified as pions or kaons according to a kaon to pion likelihood ratio. Candidate π^0 mesons are reconstructed from pairs of photons in the ECL if the γ pairs have invariant mass inside a $\pm 3\sigma$ ($\sigma = 5.4 \text{ MeV}/c^2$) mass window around the π^0 peak. The π^0 daughter photons are required to have energies greater than 50 MeV. The π^0 s are then constrained to the nominal π^0 mass [8]. Candidate η mesons are required to have invariant masses within $\pm 2.5\sigma$ of the η peak, where σ is $10.6 \text{ MeV}/c^2$ and $3.4 \text{ MeV}/c^2$ for the $\gamma\gamma$ and $\pi^+\pi^-\pi^0$ modes, respectively. For the $\pi^+\pi^-\pi^0$ mode, the $\pi^+\pi^-$ pair is constrained to a vertex.

Both photons from the $\eta \rightarrow \gamma\gamma$ mode are required to have $E_\gamma > 100$ MeV and the energy asymmetry of the daughter photons, $\frac{|E_{\gamma 1} - E_{\gamma 2}|}{E_{\gamma 1} + E_{\gamma 2}}$, is required to be less than 0.8. We remove η candidates if either of the daughter photons can be combined with any other photon with $E_\gamma > 100$ MeV to form a π^0 candidate. The η candidates are further constrained to the known η mass [8]. Candidate ω mesons are constructed from $\pi^+\pi^-\pi^0$ combinations where the $\pi^+\pi^-$ pair must form a vertex, and the CM momentum of the π^0 is required to be greater than 350 MeV/c to reduce the large combinatorial background from low energy photons. The invariant mass of the $\pi^+\pi^-\pi^0$ combination is required to be within ± 30 MeV/c² of the nominal ω mass [8] (the natural width of the ω is 8.9 MeV/c²).

We reconstruct D^0 mesons in the $D^0 \rightarrow K^-\pi^+$, $K^-\pi^+\pi^0$, and $K^-\pi^+\pi^-\pi^+$ decay modes. The CM momentum of the π^0 from $D^0 \rightarrow K^-\pi^+\pi^0$ decay is required to be greater than 300 MeV/c. The invariant mass of the D^0 candidate is required to be within $\pm 2.5\sigma$ of the measured D^0 mass where σ , the D^0 mass resolution, varies between 5.5 and 13 MeV/c² depending on the decay mode. A mass and vertex-constrained kinematic fit is then performed on the D^0 candidates. D^{*0} candidates are reconstructed in the $D^{*0} \rightarrow D^0\pi^0$ decay mode; the minimum photon energy requirement is reduced to 20 MeV for this case. The mass difference, $\delta m = M(D^0\pi^0) - M(D^0)$, is required to be within $\pm 2.5\sigma$ ($\sigma = 0.82$ MeV/c²) of its nominal value.

We combine D^0 s or D^{*0} s with h^0 meson candidates to form \bar{B}^0 candidates. Two kinematic variables are used to identify signal candidates, the beam-constrained mass $M_{bc} = \sqrt{(E_{\text{beam}}^{\text{CM}})^2 - (p_B^{\text{CM}})^2}$ and the energy difference $\Delta E = E_B^{\text{CM}} - E_{\text{beam}}^{\text{CM}}$, where E_B^{CM} and p_B^{CM} are the CM energy and momentum of the \bar{B}^0 candidate, and $E_{\text{beam}}^{\text{CM}} = \sqrt{s}/2 = 5.29$ GeV. The typical M_{bc} resolution is 3 MeV/c²; the ΔE resolution ranges from 17 to 35 MeV, depending on the decay mode. When more than one \bar{B}^0 candidate is found in an event, the candidate with the minimum χ^2 is chosen, where $\chi^2 = \chi_{D^0}^2 + \chi_{h^0}^2 (+\chi_{\delta m}^2)$. Here $\chi_{D^0}^2$ is from the kinematic fit to the D^0 , $\chi_{h^0}^2$ is from the kinematic fit to the h^0 for the π^0 or the η , while $\chi_{h^0}^2 = (\Delta(M_\omega)/\sigma(M_\omega))^2$ for the ω . Here $\Delta(M_\omega)$ is the mass difference between measured and nominal mass values and $\sigma(M_\omega)$ is the measured resolution. For the $D^{*0}h^0$ modes, $\chi_{\delta m}^2$, defined as $(\Delta(\delta m)/\sigma(\delta m))^2$, is included in the best candidate selection.

The background from continuum $e^+e^- \rightarrow q\bar{q}$ production is suppressed in the following way. We form a Fisher discriminant [9] containing seven variables that quantify event topology. The Fisher variables include the angle between the thrust axis [10] of the B candidate and the thrust axis of the rest of the event ($\cos\theta_T$), the S_\perp variable [11], and five modified [12] Fox-Wolfram moments [13]. In the $D^{*0}\pi^0$ and $D^0\omega$ modes, helicity provides additional discrimination. For the $D^{*0}\pi^0$ mode, we define $\mathcal{H}_{D^{*0}}$ as the cosine of the angle between the D^{*0} flight direction and the direction of the π^0 in the D^{*0} rest frame and require $|\mathcal{H}_{D^{*0}}| > 0.4$. For the $D^0\omega$ mode, we define \mathcal{H}_ω as the cosine of the angle between the B flight direction and the normal to the ω decay plane in the ω rest frame. We also define a variable \mathcal{A} as the absolute value of the cross product of the two charged pion momentum vectors, $|\vec{P}_{\pi^+} \times \vec{P}_{\pi^-}|$, in the ω rest frame. To suppress the $q\bar{q}$ background, we take the B flight direction and the Fisher discriminant, and for modes with ω mesons we include the variable \mathcal{A} . For the $D^0\omega$ mode, we also include the variable \mathcal{H}_ω . These variables are then combined to form signal (S) and background (BG) probability density functions (PDFs). Signal PDFs are determined using Monte Carlo (MC), and background PDFs are obtained from M_{bc} sideband data. The PDFs are multiplied to form a signal (background) likelihood

$\mathcal{L}_{\text{S(BG)}}$, and a selection is applied on the likelihood ratio $\mathcal{L}_{\text{S}}/(\mathcal{L}_{\text{S}} + \mathcal{L}_{\text{BG}})$. This requirement, which has a typical efficiency of 70%, removes more than 90% of the $q\bar{q}$ background.

In addition to the $q\bar{q}$ background, there are large background contributions from color-favored $B \rightarrow D^{(*)}(n\pi)^-$ decays and feed-down from $D^{*0}h^0$ to D^0h^0 modes. The color-favored $B \rightarrow D^{(*)}(n\pi)^-$ events give rise to two kinds of backgrounds: those with the same final state particles as signal events, and those with missing or extra particles. The former mimics the signal distributions in both M_{bc} and ΔE , and selection cuts on variables other than these (discussed below) are needed to suppress these backgrounds. The backgrounds with different final state particles arise when a pion is missed or a spurious pion is added. In this case, the background events may not be distinguishable in the M_{bc} distribution if the missing or extra pion has very low momentum, but the ΔE distribution provides a useful discriminant because of the missing pion rest-mass energy.

The $\bar{B}^0 \rightarrow D^{*+}\rho^-$ mode can give the same final states as $D^0\omega$ and $D^0\eta$. However, more than 99% of the background events are removed by the ω and η mass cuts since the invariant mass of the three pions rarely falls within the ω or η mass region.

The $B^- \rightarrow D^{(*)0}\rho^-$ final state can contaminate the $D^{(*)0}\pi^0$ mode if the ρ^- decay produces a fast π^0 . The background events from $D^0\rho^-$ to $D^0\pi^0$ ($D^{*0}\rho^-$ to $D^{*0}\pi^0$) have ΔE values that are below the signal region because of the slow π^- that is missed in the reconstruction. However, the signal contamination is not negligible due to the large branching fraction of $B^- \rightarrow D^{(*)0}\rho^-$. The $D^0\rho^-$ mode can also cause a background to $D^{*0}\pi^0$ if a low momentum π^0 is used to form a D^{*0} candidate. This case is similar to the case where the final state particles are the same, and causes a few events in the signal region. About half of these events are removed by rejecting events that can be reconstructed as $B^- \rightarrow D^{(*)0}\rho^-$. This reduces the systematic error when fitting for the signal yields and only removes a few percent of signal events.

The $B^- \rightarrow D^{(*)0}\rho^-$ mode can also contaminate the $D^{(*)0}\eta$ channel if a photon from the fast π^0 is combined with another photon to form an η candidate. The contributions of these backgrounds in the η channel, as well as the feed-across from the $D^{(*)0}\pi^0$ mode, are minimized by the π^0 veto described earlier.

We also check the background contributions from $B^- \rightarrow D^{(*)0}\rho'^- (\rho'^- \rightarrow \omega\pi^-)$ decays that have been reported recently by the CLEO Collaboration [14]. This two-body decay produces high momentum $D^{(*)0}$ s and ω s that may fake signal events. Monte Carlo studies indicate that the remaining background events are shifted in ΔE by more than the mass of the missing pion and thus are distinguished from signal events by the fit to the ΔE distribution. The $D^0\rho'^-$ mode can also contaminate the $D^{*0}\omega$ mode if the π^- from ρ'^- is replaced by a π^0 . However, since the π^- from ρ'^- decay carries sizable momentum, the kinematics of the final state particles are different from that of the $D^{*0}\omega$ signal, and the expected background is small.

The ΔE distributions for the various $D^{(*)0}h^0$ decays, after the application of all selection requirements and with M_{bc} between 5.27 GeV/ c^2 and 5.29 GeV/ c^2 , are shown in Fig. 2. The plots are fitted to the signal and background functions using a binned maximum likelihood. The signal shape is an empirically determined parameterization [15] with parameters obtained via MC. We observe good agreement between data and MC for the ΔE distributions of color-favored decays such as $D^{*+}\rho^-$ and $D^0\rho^-$. The background functions include a combinatorial component and a color-favored component. For the D^0h^0 modes, we also include a

component for feed-down from color-suppressed $D^{*0}h^0$ modes. The contribution from $D^{*0}h^0$ to D^0h^0 modes is found to be negligible. The combinatorial component is taken to be a first-order polynomial with a slope determined from the ΔE shape of the M_{bc} sideband ($5.20 \text{ GeV}/c^2 < M_{bc} < 5.26 \text{ GeV}/c^2$) data. The shapes of the color-favored and feed-down components are modeled by MC. The area of the feed-down component from $D^{*0}h^0$ to D^0h^0 is fixed by the obtained signal yield from $D^{*0}h^0$ with the estimated feed-down efficiency in MC. For the $D^{(*)0}\omega$ mode, the $D^{(*)0}\rho'^-$ components are also fixed by MC using the measured branching fractions [14]. The normalizations of the signal and background components are free parameters.

Table I lists the signal yield, statistical significance, reconstruction efficiency, and branching fraction for each $D^{(*)0}h^0$ mode. In addition, the estimated number of events in the region of $-0.1 \text{ GeV} < \Delta E < 0.1 \text{ GeV}$ due to backgrounds from generic $B\bar{B}$ decays, $D^{*0}h^0$ feed-down, and $q\bar{q}$ production are given. The systematic errors due to fitting are obtained by varying the parameters of the fitting functions within 1σ of their nominal values. The change in the signal yield from each variation is added in quadrature to obtain systematic errors from the fit. These are between 5% and 15% depending on the decay mode. The statistical significance is defined as $\sqrt{-2\ln(\mathcal{L}(0)/\mathcal{L}_{\max})}$ where \mathcal{L}_{\max} is the likelihood at the nominal signal yield and $\mathcal{L}(0)$ is the likelihood with the signal yield fixed to zero. We observe signals for $\bar{B}^0 \rightarrow D^0\pi^0$, $D^{*0}\pi^0$, $D^0\eta$, and $D^0\omega$ decays with more than 4σ significance. Independent fits to the M_{bc} distributions, after subtracting $B\bar{B}$ background, confirm these results. We find evidence for $\bar{B}^0 \rightarrow D^{*0}\eta$ and $D^{*0}\omega$ with more than 3σ significance. For decay modes with significance less than 4σ , we give 90% confidence level upper limits (UL) on the signal yields (N_S^{UL}) from the relation $\int_0^{N_S^{\text{UL}}} \mathcal{L}(N_S) dN_S / \int_0^\infty \mathcal{L}(N_S) dN_S = 0.9$, where $\mathcal{L}(N_S)$ denotes the maximum likelihood with the signal yield fixed at N_S .

The efficiencies for each mode are obtained by Monte Carlo and calibrated by a detailed study of detector performance. In particular, studies of tracking, π^0 detection, and particle identification give systematic errors in the detection efficiencies of low momentum π^0 , energetic π^0 , η , and ω mesons of 10.7%, 7.3%, 9.6%, and 9.5% respectively. The systematic error on the D^0 meson reconstruction efficiency is estimated to be 12.7% by comparing the observed yield of $B^- \rightarrow D^0\pi^-$ events with the expected yield using known branching fractions [8]. A 5% systematic error on the likelihood ratio requirement is determined by applying the same procedure to the $B^- \rightarrow D^{*0}\pi^-$ sample and comparing the effects on data and MC. The final systematic errors of the branching fractions include the errors in fitting, reconstruction efficiency, cut efficiency for background suppression, and the number of $B\bar{B}$ pairs. Assuming the number of $B^0\bar{B}^0$ and B^+B^- pairs to be equal, we calculate the branching fractions for various decay modes given in Table I. The branching fraction upper limits are calculated by increasing N_S^{UL} and reducing the efficiency by their systematic errors.

Our measurement of $\mathcal{B}(\bar{B}^0 \rightarrow D^0\pi^0) = (3.1 \pm 0.4 \pm 0.5) \times 10^{-4}$ is above the previous UL of 1.2×10^{-4} obtained by CLEO [1]. It is also considerably higher than the factorization prediction of 0.7×10^{-4} [2]. This could indicate the presence of final state interactions, or other corrections to factorization. It is customary to decompose [2] the $B^- \rightarrow D^0\pi^-$ and $\bar{B}^0 \rightarrow D^+\pi^-$, $D^0\pi^0$ decay amplitudes into isospin $\frac{1}{2}$ and $\frac{3}{2}$ components. Our measurement of $\mathcal{B}(\bar{B}^0 \rightarrow D^0\pi^0)$, together with the known branching fractions [8] of the other two modes, suggest a rescattering phase difference between isospin $\frac{1}{2}$ and $\frac{3}{2}$ amplitudes that is $31^\circ \pm 7^\circ$. A similar value, $32^\circ \pm 8^\circ$, is obtained for the $\bar{B} \rightarrow D^*\pi$ system.

Our measurements of $\mathcal{B}(\overline{B}^0 \rightarrow D^0 \eta) = (1.4^{+0.5}_{-0.4} \pm 0.3) \times 10^{-4}$ and $\mathcal{B}(\overline{B}^0 \rightarrow D^0 \omega) = (1.8 \pm 0.5^{+0.4}_{-0.3}) \times 10^{-4}$ are also higher than the factorization predictions of 0.5×10^{-4} and 0.7×10^{-4} [2]. The central values of the two less significant modes show the same pattern. The results for these modes cannot be accommodated by the aforementioned elastic rescattering phase.

In summary, using 23.1 million $B\overline{B}$ events collected with the Belle detector, we report the first observations of color-suppressed $\overline{B}^0 \rightarrow D^0 \pi^0$, $D^{*0} \pi^0$, $D^0 \eta$, and $D^0 \omega$ decays, and evidence for $\overline{B}^0 \rightarrow D^{*0} \eta$ and $D^{*0} \omega$ modes. All these modes have similar branching fractions with central values between 1.4×10^{-4} and 3.1×10^{-4} , as given in Table I. They are all consistently higher than recent theoretical predictions based on the factorization hypothesis. This may be accounted for by additional corrections to the factorization models, or by non-factorizable effects such as final state interactions.

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TABLE I. The obtained signal yields, statistical significances (Σ), background events from generic $B\bar{B}$ decays ($B\bar{B}$ bg), $D^{*0}h^0$ feed-down ($D^{*0}h^0$), and $q\bar{q}$ production ($q\bar{q}$ bg), reconstruction efficiencies (ϵ) (including the sub-decay branching fractions), branching fractions (\mathcal{B}), and 90% confidence level upper limits (UL) for $\bar{B}^0 \rightarrow D^{*0}\eta$ and $D^{*0}\omega$ are listed together with the theoretical predictions (Th) [2]. The background events are estimated under the signal peak (in the region of $-0.1 \text{ GeV} < \Delta E < 0.1 \text{ GeV}$).

Mode	Signal Yield	Σ	$B\bar{B}$ bg	$D^{*0}h^0$	$q\bar{q}$ bg	$\epsilon(\%)$	$\mathcal{B} (\times 10^{-4})$	UL ($\times 10^{-4}$)	Th ($\times 10^{-4}$)
$D^0\pi^0$	$126.2^{+16.1}_{-15.5}^{+7.2}_{-5.2}$	9.3	26.7	1.3	145.6	1.79	$3.1 \pm 0.4 \pm 0.5$	—	0.7
$D^{*0}\pi^0$	$26.4^{+7.7}_{-7.1}^{+1.6}_{-2.2}$	4.1	5.9	—	10.4	0.42	$2.7^{+0.8}_{-0.7}^{+0.5}_{-0.6}$	—	1.0
$D^0\eta^*$	$22.1^{+7.0}_{-6.3}^{+2.0}_{-1.8}$	4.2	3.4	0.7	19.1	0.67	$1.4^{+0.5}_{-0.4} \pm 0.3$	—	0.5
$D^{*0}\eta$	$7.8^{+3.6}_{-3.0} \pm 0.7$	3.3	1.4	—	1.5	0.17	$2.0^{+0.9}_{-0.8} \pm 0.4$	4.6	0.6
$D^0\omega$	$32.5^{+9.4}_{-8.6}^{+4.0}_{-3.1}$	4.4	$5.3(2.3)^\dagger$	1.4	58.5	0.80	$1.8 \pm 0.5^{+0.4}_{-0.3}$	—	0.7
$D^{*0}\omega$	$16.1^{+6.8}_{-6.0} \pm 2.4$	3.0	$5.3(1.5)^\dagger$	—	13.8	0.23	$3.1^{+1.3}_{-1.1} \pm 0.8$	7.9	1.7

* For decay modes with η mesons, about 70% of the signal is reconstructed in the $\gamma\gamma$ channel and the remainder is in the $\pi^+\pi^-\pi^0$ channel. † The values in parentheses are the estimated background from $B^- \rightarrow D^{(*)0}\rho'^-$ decays.

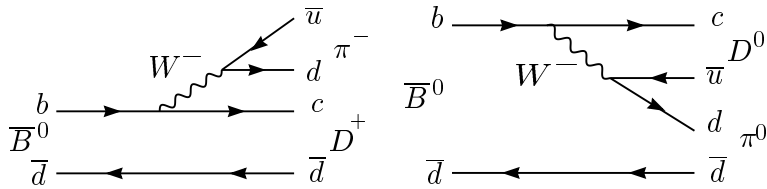


FIG. 1. The external (left) and internal (right) spectator diagrams for $\bar{B} \rightarrow D\pi$ decays.

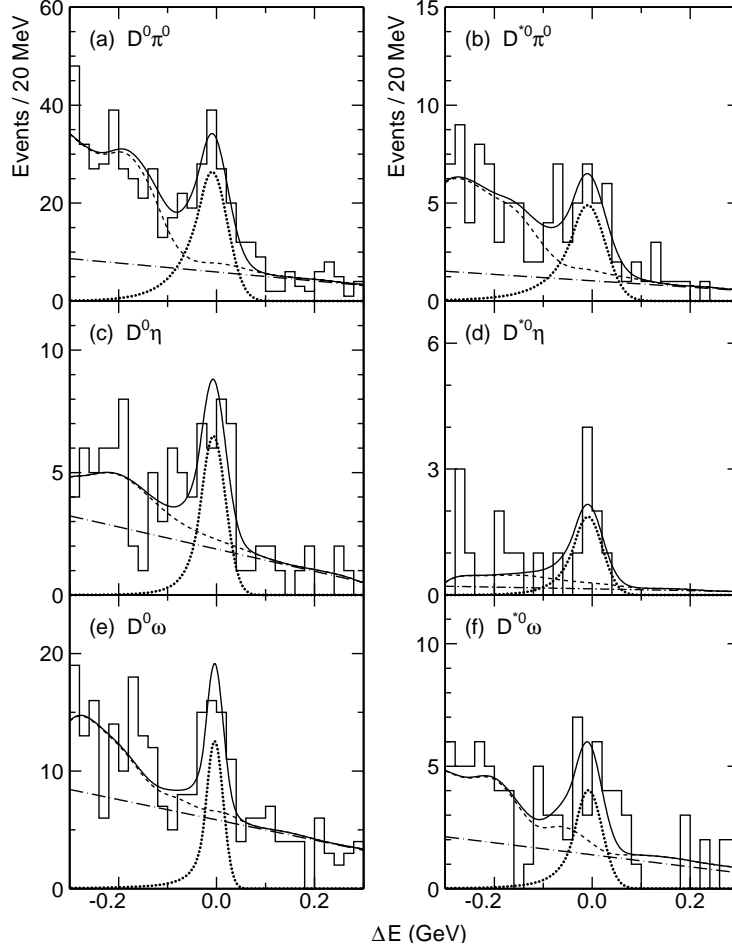


FIG. 2. The ΔE distributions for (a) $D^0\pi^0$, (b) $D^{*0}\pi^0$, (c) $D^0\eta$, (d) $D^{*0}\eta$, (e) $D^0\omega$, and (f) $D^{*0}\omega$. The solid lines show the fit results, the dotted lines are the signals, and the dashed lines show the sum of the feed-across and the combinatorial background, with the latter shown separately as the dash-dotted lines.